

NAVAL SYSTEMS ENGINEERING DEPARTMENT
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Research Report EW-6-87

ABSORPTION CAPABILITY OF CO₂
SCRUBBERS UNDER VARIABLE
METABOLIC LOADINGS

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6 May 1987

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ABSTRACT

The objective of this project was to demonstrate the effects of varying metabolic loadings on the absorption capability of carbon dioxide scrubbers. The study's main purpose was to determine whether prebreathing a canister, that is, subjecting it to a low initial CO₂ loading, would result in a longer lifetime for the canister. At present there exists no means for predicting the performance of a canister which sees non-cyclic metabolic profiles.

The experimental study was conducted in the Coastal Engineering Laboratory at the United States Naval Academy. Carbon dioxide was injected into a closed circuit system simulating the human breathing cycle. The carbon dioxide effluent level was measured with an infrared analyzer and recorded on a strip-chart recorder. Each test was continued until effluent CO₂ levels reached 1.0%.

Four CO₂ injection profiles were chosen for this experiment. Each profile was run twice, for a total of eight tests. Canister efficiency for each test was approximately 20 to 30%. For this experiment, prebreathing the canisters did not result in a longer CO₂ scrubber lifetime. The results were contrary to what was expected: the canisters which were subjected initially to low CO₂ loadings reached breakthrough time much sooner than canisters which were subjected initially to high loadings.

INTRODUCTION

The goal of air revitalization systems, such as carbon dioxide absorbing agents, is to remove metabolically produced carbon dioxide from aspired gases, and resupply life sustaining oxygen. The objective of this project is to demonstrate the effects of varying metabolic profiles on the absorption capabilities of carbon dioxide scrubbers.

Through laboratory testing in recent years, NCSC has become better equipped to make ballpark predictions of CO₂ scrubber durations under steady flow conditions where metabolic levels are uniform. Some success has been obtained in applying these prediction methods to variable metabolic profiles which are cyclic in behavior (such as the NEDU cyclic profile having six minutes of work followed by four minutes of rest).

At present time, however, there exists no means for predicting the performance of a canister which sees non-cyclic metabolic profiles. Such profiles occur frequently in underwater missions due to the wide range of tasks that a diver is called on to do in any single mission. A diver may be required to perform at extremely high activity levels for short durations, only to wait out a lengthy decompression stage at rest.

Researchers at NCSC, NEDU, NASA, and others have made the following qualitative observations when dealing with these profiles:

a.) Canisters having low, initial metabolic inputs followed by increased CO₂ loadings show improved performance over canisters which see high loadings at the beginning of the mission. NASA has recorded up to 11 hour durations with their Extravehicular Mobility Unit (EMU) canister (designed for 7 hour missions) when the canister is "prebreathed" for 3 1/2 hours prior to the initiation of the mission. Only 7-8 hour mission durations are recorded without prebreathing.

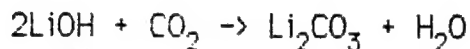
b.) Canisters which experience breakthrough following high metabolic loadings have been observed to "recover" following a period of inactivity. Canisters which were allowed to remain dormant overnight following breakthrough in the NCSC Gas Laboratory were found to absorb an additional amount of CO₂ approaching that initially absorbed prior to breakthrough.

c.) Dual, parallel canisters through which exhaust gases are alternately switched have been observed to out perform a single canister through which CO₂-laden gases continually flow. This phenomenon may be related to the ability of chemical absorbers to recover when inactive.

This effort is intended to quantify the effects of these non-cyclic metabolic loadings on the absorption capability of carbon dioxide scrubbers.

DISCUSSION OF THEORY

Carbon dioxide scrubbing materials can be classified with respect to their physical and chemical properties, and their function and scrubbing mechanism. For this experiment, lithium hydroxide (LiOH) is used as the carbon dioxide scrubbing material. Lithium hydroxide belongs to a group of scrubbing materials which are classified as alkali metal hydroxides. Alkali metal hydroxides react with carbon dioxide to form carbonate, bicarbonate, or hydrates of carbonates and bicarbonates. Lithium hydroxide is a promising agent because of its high theoretical capacity to absorb carbon dioxide. The theoretical capacity of lithium hydroxide is calculated based on the following net reaction:



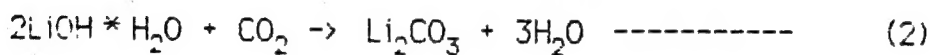
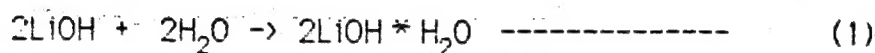
Since lithium hydroxide reacts with carbon dioxide in a two to one ratio.

$$\frac{1 \text{ mole CO}_2}{2 \text{ mole LiOH}} \times \frac{44 \text{ lb. CO}_2 / 1 \text{ mole CO}_2}{2 * 23.94 \text{ lb. LiOH} / 2 \text{ mole LiOH}} = 0.919 \frac{\text{lb. CO}_2}{\text{lb. LiOH}}$$

Thus, one pound of lithium hydroxide has the theoretical capacity to absorb 0.919 lbs. of carbon dioxide. Other alkali metal hydroxides also

have a high capacity for carbon dioxide. Their high degree of hygroscopicity, however, eliminates them from consideration as solid absorbents. Experience has shown that CO₂ removal is related to many factors such as porosity, granule size, surface area, moisture content, scrubber design and other environmental conditions such as temperature, humidity, pressure, etc.

Lithium hydroxide absorbs carbon dioxide from a gas mixture in the presence of water vapor. The reaction is given according to the following equations :



The reaction of CO₂ with LiOH requires the presence of water in an amount sufficient to produce LiOH · H₂O prior to or simultaneously with the CO₂ reaction. Insufficient water vapor in the air stream allows only partial CO₂ reactions, while an excessive amount of water vapor forms a water film barrier around the absorbent granules also resulting in an incomplete reaction between CO₂ and absorbents.

The theoretical bed life (TBL) of a canister is the length of time the CO₂ scrubbing agent is able to absorb carbon dioxide. TBL can be calculated in the following manner. The volume of the canister for this

experiment is approximately 55 cubic inches, and the density of lithium hydroxide is 0.01551 lb./ in³. The canister can therefore hold:

$$55 \text{ cubic inches} * 0.1551 \text{ lbs. LiOH/ cubic inch} = 0.85 \text{ lbs. LiOH}$$

and can theoretically absorb:

$$0.85 \text{ lbs. LiOH} * 0.919 \text{ lbs CO}_2 / \text{lb. LiOH} = 0.781 \text{ lbs. CO}_2.$$

The theoretical bed life is determined based on the carbon dioxide injection rate. For an injection rate of 1.0 SLPM of CO₂:

$$\left(\frac{1.0 \text{ liters CO}_2}{\text{min.}} \right) \left(\frac{\text{ft}^3 \text{ CO}_2}{28.3 \text{ liter CO}_2} \right) \left(\frac{0.123 \text{ lb. CO}_2}{\text{ft}^3 \text{ CO}_2} \right) \left(\frac{60 \text{ min.}}{\text{hr.}} \right) = 0.261 \frac{\text{lbs. CO}_2}{\text{hr.}}$$

The theoretical bed life (TBL) would be:

$$\frac{0.781 \text{ lbs. CO}_2}{0.261 \text{ lbs. CO}_2 / \text{hr}} = 3.0 \text{ hrs.}$$

The efficiency of a canister is calculated by dividing the breakthrough time by the theoretical bed life. Breakthrough is defined as the time it takes a canister to reach an effluent CO₂ level of 0.5%. Thus, to find efficiency:

$$\text{efficiency} = \frac{\text{time to breakthrough}}{\text{TBL}}$$

Prior to beginning tests on the absorption rate of the CO₂ scrubber, specific CO₂ injection profiles are chosen. The CO₂ injection rate simulates the rate of carbon dioxide generated in the human body as cells burn oxygen and nutrients. The rate of oxygen used by the cells is referred to as the oxygen consumption rate, \dot{V}_{O_2} . The amount of oxygen metabolized at the cells during the combustion of proteins, fats, and carbohydrates will vary with activity level; ranging from approximately 0.25 SLPM for a resting person, upwards to 3 SLPM for short duration, extremely hard activities.

The ratio of carbon dioxide generation (\dot{V}_{CO_2}) to oxygen consumption is called the respiratory quotient (RQ). That is:

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}}$$

Values for RQ change under different metabolic conditions. When a person is consuming carbohydrates entirely for body metabolism, RQ is about 1.00. However, when a person utilizes fats almost entirely for metabolism, the RQ falls to 0.7. A person on a normal diet of carbohydrates, fats and proteins has an RQ of approximately 0.825. The value of RQ chosen for this experiment is 0.80.

The total amount of new gas moved into the respiratory passages of the body each minute is called the Respiratory Minute Volume (RMV). The

respiratory minute volume is equal to the tidal volume, or lung volume during a single breathing cycle, times the respiratory rate. That is:

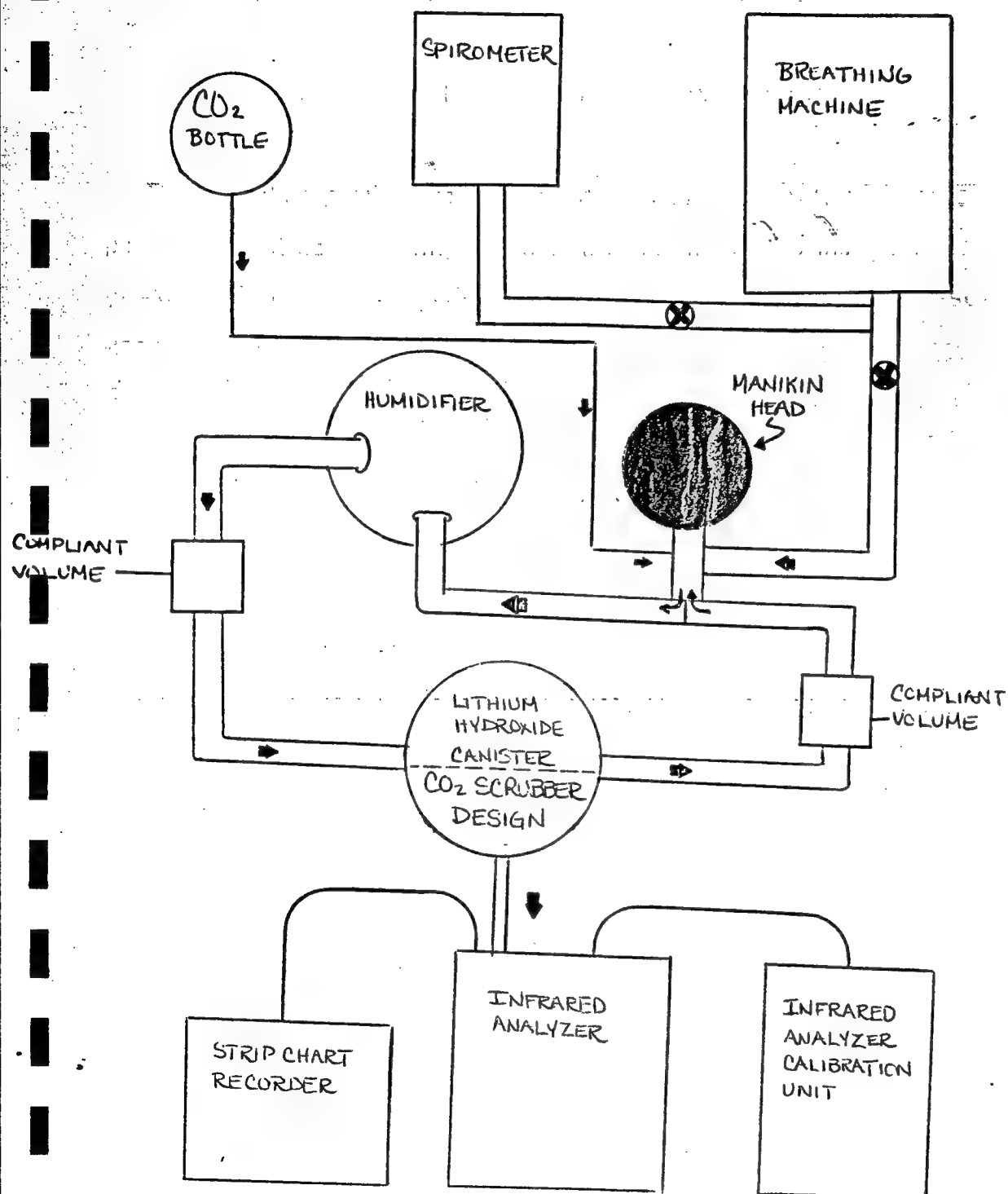
$$\text{RMV (liters/minute)} = \text{TV (liters/breath)} * \text{RR (breaths/minute)}$$

The normal respiratory rate for an adult is approximately 12 breaths per minute, but can go as high as 30 breaths per minute during heavy exercise. Therefore, RMV's range from about 6 liters per minute at rest to about 90 liters per minute during heavy work. It has been observed that RMV is related to the rate of oxygen consumption by:

$$\frac{\text{RMV (ALPM)}}{\dot{V}_{O_2} \text{ (SLPM)}} = 24$$

For this experiment, the air and carbon dioxide in the closed loop of the system circulate at a rate based on the rate of oxygen consumption and the respiratory minute volume.

EXPERIMENTAL SET-UP CLOSED-LOOP CIRCUIT



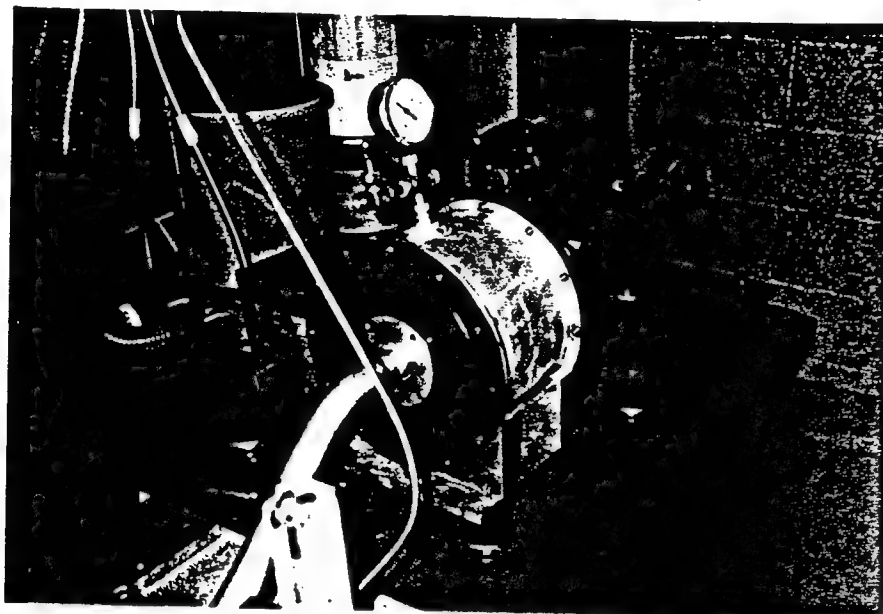
DESCRIPTION OF APPARATUS

The experimental set-up consists of a closed-loop circuit which simulates a breathing cycle. A breathing machine keeps the air circulating in the system. The output of the breathing machine is fed through a manikin head to a humidifier. The humidifier adds moisture and heat to the air to better simulate the human breath. From the humidifier the air goes to a compliant volume and then to the carbon dioxide scrubber design. The carbon dioxide scrubber design is a vertical canister which holds the lithium hydroxide scrubbing agent. The air enters the bottom of the canister, "percolates" through the lithium hydroxide, and exits the top of the canister to another compliant volume. After leaving the second compliant volume, the air circulates back to the manikin head.

BREATHING MACHINE

The breathing machine is the driving force in the system as it keeps air circulating around the closed loop circuit. It consists of a small motor which turns a crankshaft and pushes air in and out of a cylinder. The volume of air pushed in and out of the cylinder can be controlled by adjusting a knob on the crankshaft which effectively changes the length of the crankshaft. The rate at which the crankshaft rotates corresponds to the number of breaths per minute, and this rate can be adjusted with a knob on the control box of the machine. To ensure a tight seal in the cylinder, a pump hooked up to the cylinder creates a vacuum. A spirometer

is used to calibrate the breathing machine. Calibration procedures are discussed in appendix A.

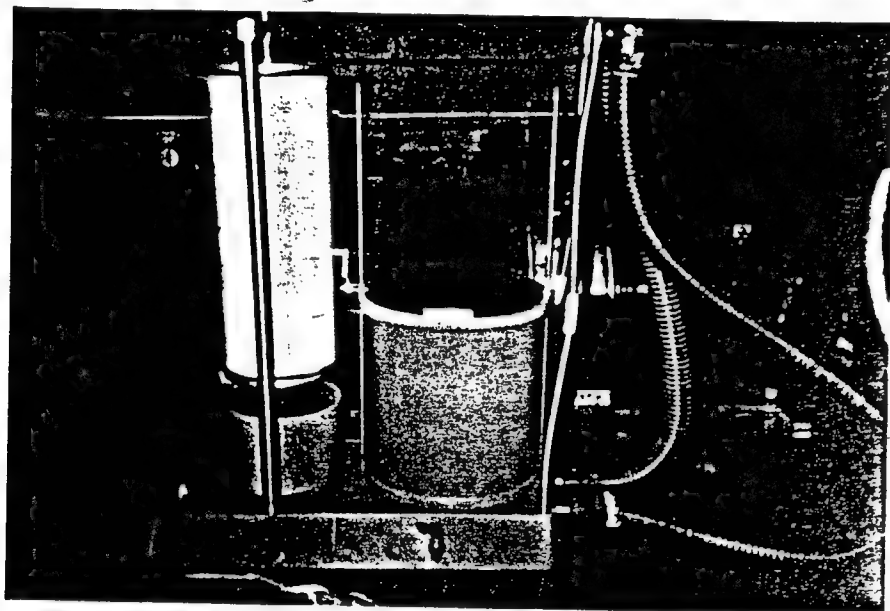


BREATHING MACHINE

SPIROMETER

A spirometer is used to calibrate the breathing machine by measuring the tidal volume it creates. The spirometer consists basically of a closed container and a circular barrel which records the tidal volume as it revolves. As the cylinder of the breathing machine pushes air into the container of the spirometer, the lid of the container rises up an amount corresponding to the volume of air in the cylinder of the breathing machine. Attached to the lid of the container is a pen. The pen rises up

and down as the breathing machine cylinder pushes air in and out of the container. The circular barrel revolves as the lid rises up and down, and the pen records the tidal volume on the barrel.

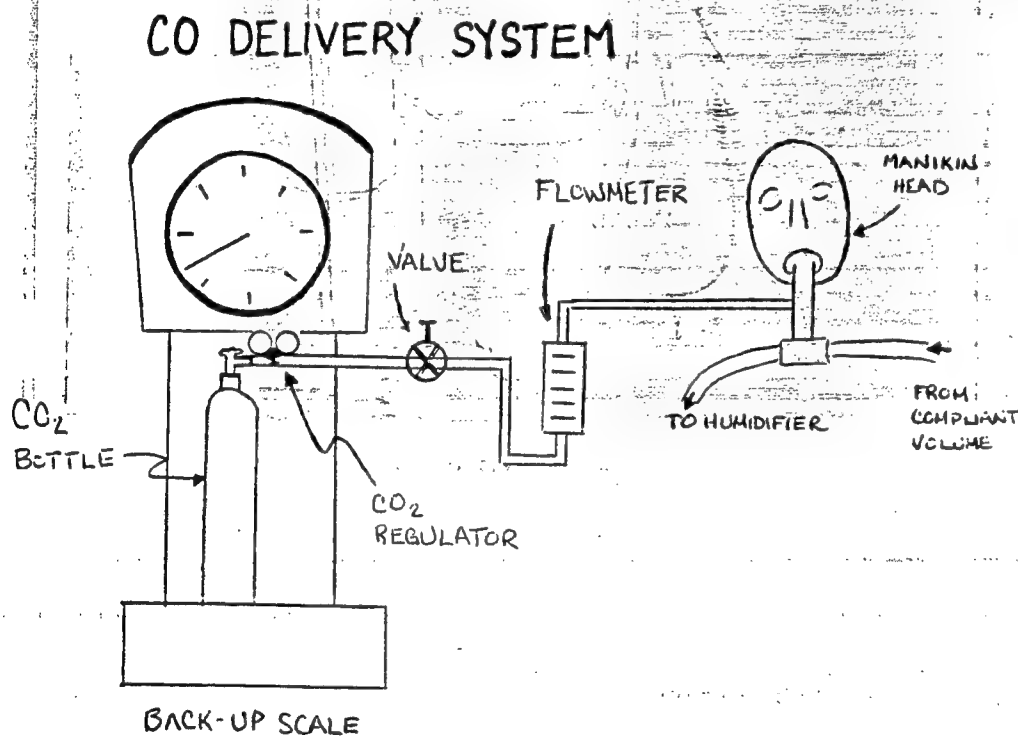


SPIROMETER

CO₂ DELIVERY SYSTEM

To simulate the carbon dioxide which is exhaled in a human breath, carbon dioxide is piped to the system through a flowmeter and fed into the tube coming out of the manikin's head. A carbon dioxide regulator and a valve located between the carbon dioxide bottle and the flowmeter help control the flow rate of CO₂ to the system. The carbon dioxide bottle sits on a scale during the experiment. As each test uses approximately 1/4 to

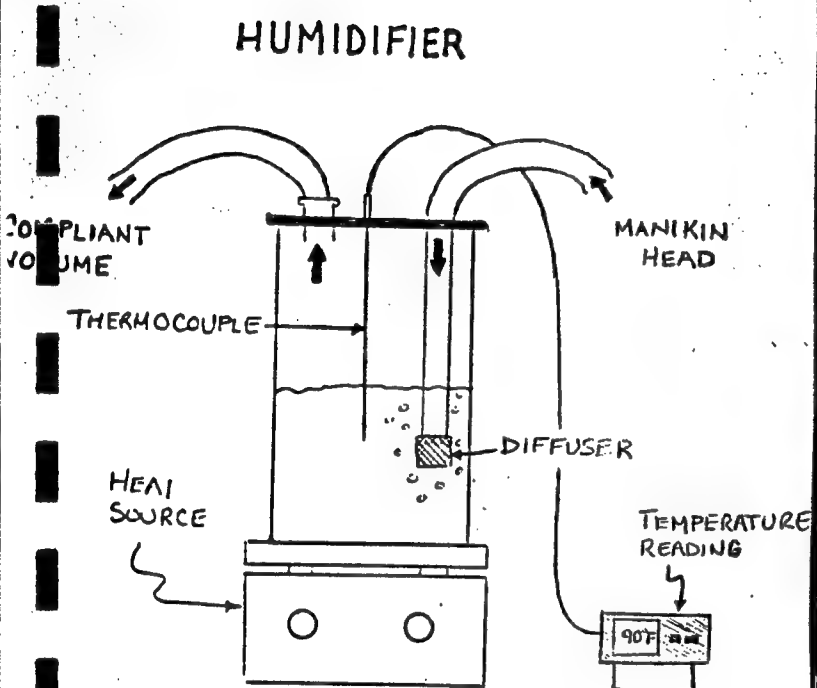
1/2 pound of carbon dioxide, the scale serves as a crude check on the flow rate. The flowmeter used for the CO₂ delivery system is a Dwyer "visi-float" flowmeter with a range of 0-4 SLPM. To measure the flow of carbon dioxide a conversion based on the specific gravity of carbon dioxide is used (The meter reading equals the desired flow rate times the square root of 1.517).



HUMIDIFIER

The humidifier is a closed, circular container filled half-way with water. The humidifier serves two purposes in the circuit. First, the humidifier adds moisture and heat to the air to simulate a human breath.

It also serves to mix the CO₂ into the circulating air. As the air flows into the humidifier, a mesh screen attached to the end of the tubing diffuses the carbon dioxide and air. The carbon dioxide then bubbles through the water to the top of the circular container and then on to the compliant volume.



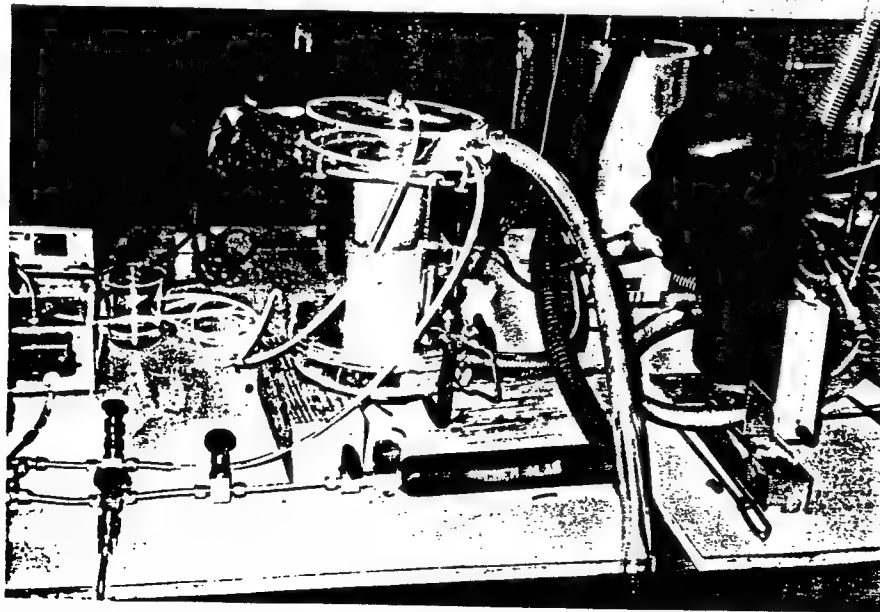
COMPLIANT VOLUMES

The compliant volumes are Mk 6 UBA breathing bags. They are attached to the side of the table to hang in a vertical position. The vertical position allows any condensate to fall to the bottom of the bag where it can drain out of a small outlet after each test run.

LITHIUM HYDROXIDE CANISTER

The canister used for this project is an experimental design made of a 1/4 inch clear plastic material. For this experiment, the lithium hydroxide is placed in the center section of the canister. This section has a volume of approximately 55 cubic inches. The procedure for filling the canister with lithium hydroxide can be found in appendix B. The canister is placed in a vertical position to avoid channeling. The air enters the bottom of the canister from the humidifier and exits the top of the canister to the second compliant volume.

The difference in pressure between the top and bottom of the canister is monitored throughout the experiment and recorded on the upper channel of the strip chart recorder. The pressure differential is measured because a dramatic increase in pressure due to a build up of reaction products in the canister is undesirable. A Validyne pressure transducer is used for this experiment.



INFRARED ANALYZER

To measure the breakthrough time of the CO₂ scrubbing material in the canister, a sample is continuously pulled off of the canister and run through a flowmeter into the infrared analyzer. The instrument used to measure flow into the infrared analyzer is a Dwyer "visi-float" flowmeter with a range of 0 to 1.0 SLPM. The sample is fed to the analyzer at a rate of 500 cc/min. The analyzer used for this experiment is the Beckman Industrial Model 864 Non-dispersive Infrared Analyzer. The calibration technique used for this experiment is explained in Appendix C.

The analyzer itself is not equipped to keep a flow circulating through the machine. For this reason, a small pump is connected to the outlet of the infrared analyzer. The pump is simply an aquarian pump converted for use in this experiment.

PROCEDURE

The first step of the experiment is to fill the canister with lithium hydroxide and connect it to the system. Before running any tests for the experiment, it is necessary to calibrate the breathing machine and infrared analyzer. The heat on the humidifier should also be turned on to allow the temperature to reach at least 90°F. Following calibration of the instruments, it is important to ensure that the system is a closed circuit. This is accomplished by spraying a low-viscous fluid on all the fittings of the tubing in the circuit. If no air bubbles through a connection, an air-tight seal can be assumed.

At this point, the carbon dioxide is allowed into the system. For this experiment, four carbon dioxide injection profiles are chosen:

<u>PROFILE</u>	<u>PRELOADING</u>	<u>LOADING #1</u>	<u>LOADING #2</u>
1	NONE	\dot{V}_{O_2} =1.0 SLPM To Breakthrough	NONE
2	1 HOUR at \dot{V}_{O_2} =0.25 SLPM	\dot{V}_{O_2} =1.0 SLPM To Breakthrough	NONE
3	NONE	\dot{V}_{O_2} =1.5 SLPM For half duration of Profile #1	\dot{V}_{O_2} =0.5 SLPM To Breakthrough
4	NONE	\dot{V}_{O_2} =0.5 SLPM For half duration of Profile #1	\dot{V}_{O_2} =1.5 SLPM To Breakthrough

The following parameters for respiratory minute volume (RMV), tidal volume (TV), and respiratory rate (RR) are also chosen for each rate of oxygen consumption:

<u>Vo2</u> <u>(SLPM)</u>	<u>Vco2</u> <u>(SLPM)</u>	<u>RMV</u> <u>(liters/min.)</u>	<u>TV</u> <u>(liters/breath)</u>	<u>RR</u> <u>(breaths/min.)</u>
0.25	0.2	6	0.5	12
0.50	0.4	12	1.0	12
1.00	0.8	24	1.5	16
1.50	1.2	36	2.0	18

Each carbon dioxide profile is continued until the canister effluent level reaches 1.0%. At this time the carbon dioxide flow is stopped and the test is finished. At the conclusion of each test, the breathing machine and infrared analyzer are re-calibrated. The lithium hydroxide canister can then be emptied and refilled for the next test.

RESULTS

PROFILE	Wt. LiOH (lbs.)	Preload V _{O2} (SLPM)	Time to 0.5% (min.)	Time to 1.0% (min.)	EFFICIENCY (%)
=====					
1					
RUN #1	0.77	none	57	60	27.9
RUN #2	0.88		50	53	21.5

2					
RUN #1	0.84	0.25 SLPM	90	96	20.2
RUN #2	0.86	for 1 hr.	102	108	27.7

3					
RUN #1	0.81	1.5 SLPM	94	97	35
RUN #2	0.86	for 28 min.	86	86	31.2

4					
RUN #1	0.84	0.5 SLPM	46.5	48.5	18.9
RUN #2	0.86	for 28 min.	44.5	46.5	17.0

CONCLUSIONS

The results of this experiment were contrary to what was expected. At an oxygen consumption rate of 1.0 SLPM, the canister experienced breakthrough after approximately one hour's time. When the canister was prebreathed for an hour at 0.25 SLPM, it was

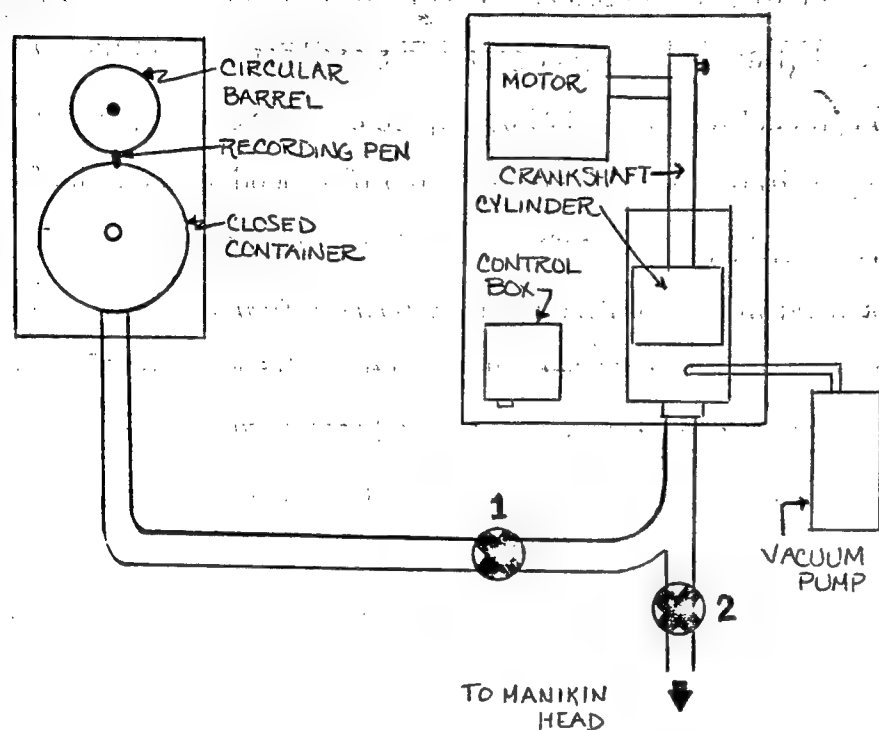
expected that the canister would then last longer than an hour after the prebreathing. During testing, the canister only lasted approximately 30 minutes after the prebreathing.

The third and fourth profiles also yielded unexpected results. It was expected that a canister subjected initially to a low CO₂ loading would last longer than a canister subjected initially to a high CO₂ loading. The canisters subjected to high initial loadings were able to last about an hour before breakthrough following the high preload. The canisters subjected to low initial loadings, however, reached breakthrough within twenty minutes after the low preload.

The pressure differential between the top and bottom of the canister was monitored continuously throughout each test. The pressure did not increase a significant amount during any of the tests.

APPENDIX A

CALIBRATION OF THE BREATHING MACHINE



- 1.) To calibrate the breathing machine, the first step is to isolate it from the rest of the circuit. This is accomplished by opening valve 1 and closing valve 2.
- 2.) Next the pump is turned on to obtain a vacuum and tight seal in the cylinder.

3.) The motor is turned on and the crankshaft knob adjusted until the desired tidal volume is achieved. The tidal volume is read from the circular barrel.

4.) After the tidal volume is set, the respiratory rate can be fixed by adjusting a knob on the control box.

5.) The breathing machine is now calibrated and opening valve 2 and closing valve 1 will connect it to the circuit again.

APPENDIX B

LITHIUM HYDROXIDE CANISTER PROCEDURES

The lithium hydroxide for the experiment should be stored in a dry atmosphere to prevent the material from degrading. Care must be taken when loading and unloading the canister as LiOH is a toxic material. To avoid inhaling any fumes, a hood should be used when filling the canister, and a respirator worn to cover the mouth and nose. It is also recommended that gloves and protective clothing be worn.

After each test is run, it is necessary to disconnect the canister from the circuit. After the lid is removed from the top of the canister, the LiOH should be disposed of in an airtight container such as an old coffee can. It is best to avoid all contact with the chemical.

The primary concern when filling the canister is in preventing channeling. Channeling occurs when the LiOH is loosely packed and the air can form a "channel" or take the same path through the lithium hydroxide in the canister. The canister sits in a vertical position to minimize the effects of channeling, but the best guard against channeling is ensuring that the lithium hydroxide is tightly packed in the canister.

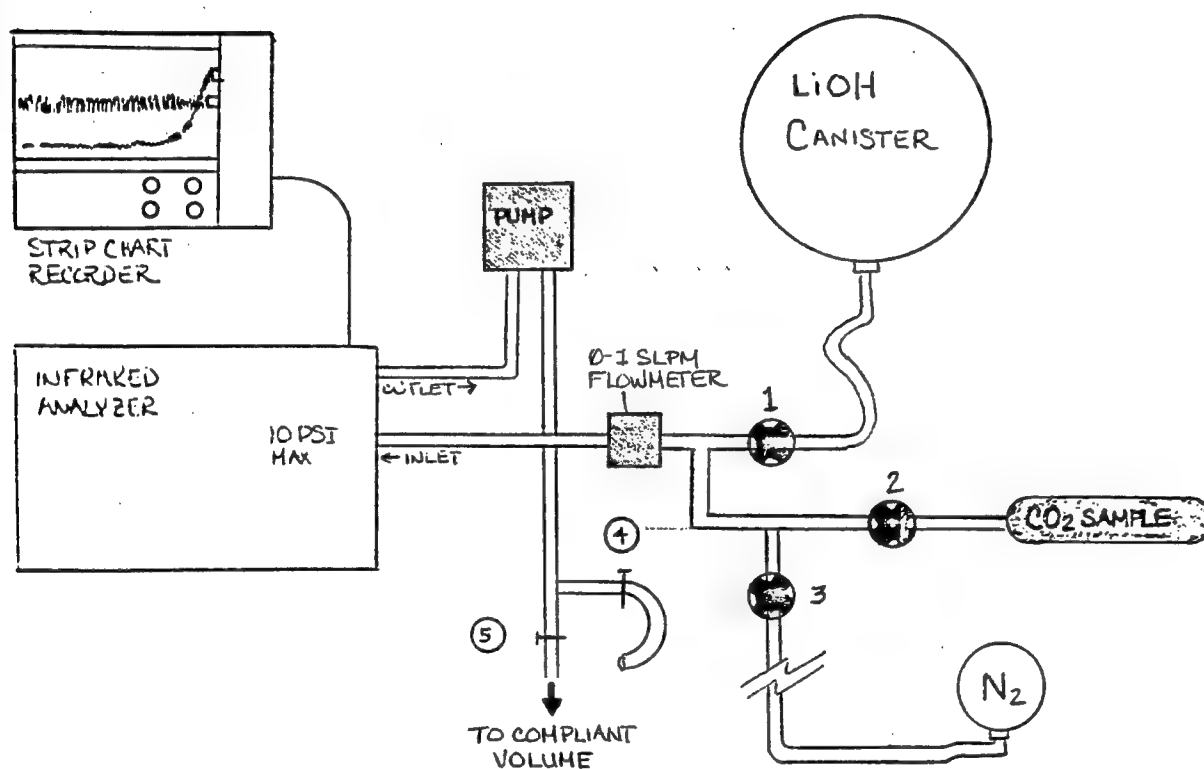
To pack the canister tightly, the lithium hydroxide is added slowly. After adding a small amount of LiOH , the canister should be shaken to allow the chemical to settle. The LiOH should be added bit by bit, each

time ensuring that the absorbing agent is settling adequately.

After filling the canister completely and weighing the new amount of LiOH, the canister is connected again to the circuit. Particular attention should be given that all the fittings and connections are airtight. For this particular experiment, C-clamps were used to hold the top of the canister securely in place.

APPENDIX C

CALIBRATION OF THE INFRARED DETECTOR AND STRIP-CHART RECORDER



- 1) For this experiment, nitrogen gas is used to obtain a zero reading on the IR detector while a 1.17% CO₂ in air mixture is used for a full scale reading
- 2) Valves 4 and 5 are turn valves which isolate the calibration unit

from the rest of the closed-circuit system. For calibration, valve 5 is closed and valve 4 remains open to allow the nitrogen and carbon dioxide gases used in the calibration to be fed out of the system into the atmosphere. This prevents even small amounts of carbon dioxide from entering the closed-circuit prior to beginning the experiment.

3.) With the range switch turned to TUNE, the analyzer is allowed to warm up for at least one hour, but preferably eight hours. The range switch is then turned to position three (Position three gives a range of 0 to 2%).

4.) With valves 1 and 2 closed and valve 3 open, nitrogen gas is fed to the IR detector at approximately 500 cc/min. for at least two minutes.

(Note: care must be taken when flowing gases through the analyzer as the maximum inlet pressure to the instrument is 10 psi.)

5.) The ZERO control is adjusted so that the meter on the IR detector reads zero.

6.) The pen of the upper channel on the strip chart recorder is also adjusted for a zero reading with nitrogen gas.

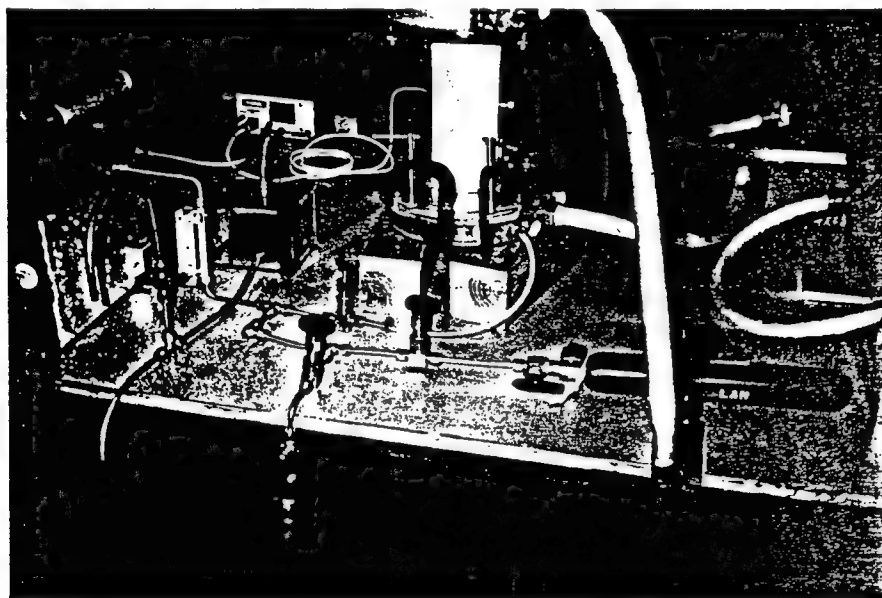
7.) Valve 3 is closed and valve 2 is opened to feed the 1.17% carbon dioxide/air mixture to the IR detector at a flow rate of approximately 500 cc/min.

8.) The pen of the strip chart recorder is then adjusted for full scale. The strip chart paper has 100 small divisions. Based on the manufacturer's non-linear calibration curves, full scale is set at 65 small divisions, which corresponds to a CO₂ percentage in air of 1.17.

9.) Valve 2 is closed and valve 3 opened to allow nitrogen gas to flow

to the IR detector at 500 cc/min. The nitrogen gas is used again to ensure that the strip chart recorder is still "zeroed-out." The pen of the recorder should fall back to zero at this point.

(10.) Once the IR detector and the strip chart recorder are calibrated, valves 2, 3, and 4 are closed, and valves 1 and 5 are opened.



INFRARED ANALYZER
CALIBRATION UNIT

APPENDIX D

STRIP-CHART RECORDER PRINT-OUTS

1051

0 10 20 30 40 50 60 70 80 90 100

100 90 80 70 60 50 40 30 20 10

PROFILE 1
RUN 1

$T_{0.5\%} = 57 \text{ min}$
 $T_{1.00\%} = 60 \text{ min}$
 $\eta = 27.9\%$

101

100 90 80 70 60 50 40 30 20 10

PROFILE 1 (RUN 2)

$T_{0.5\%} = 50 \text{ min}$

$T_{1.0\%} = 53 \text{ min}$

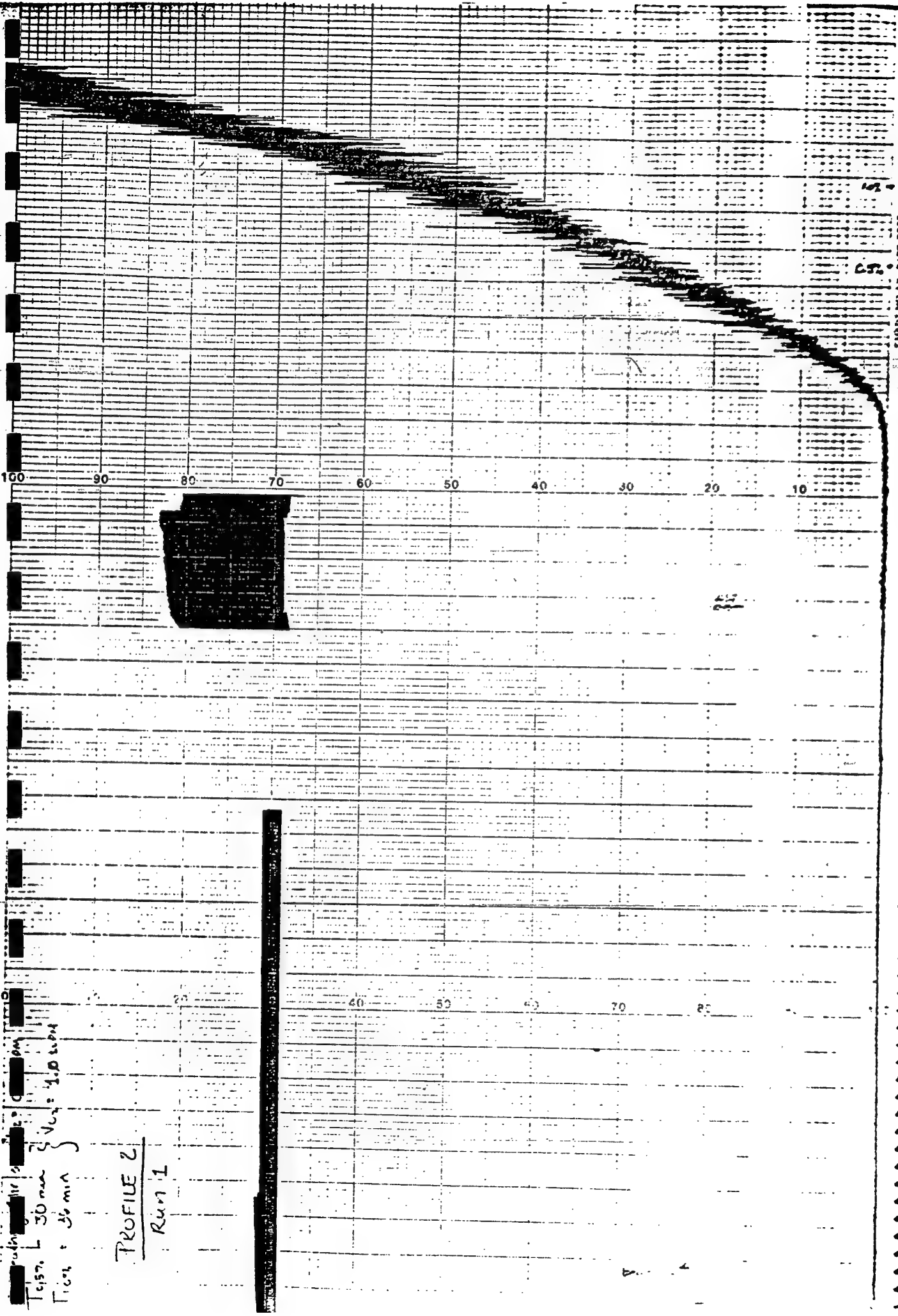
$\eta = 21.4\%$

100
90
80
70
60
50
40
30
20
10

2140
CHRY

T₁₅₇ = 30 min
 T₁₀₂ = 36 min
 V₀₂ = 1.0 L/min

PROFILE 2
 Run 1



100
 90
 80
 70
 60
 50
 40
 30
 20
 10

100 90 80 70 60 50 40 30 20 10

20 40 60 80

PROFILE 2

RUN 2

$V_{02} = 0.25 \text{ SLPM} \rightarrow 1 \text{ hr}$
 $+ 1.0 \text{ SLPM} \rightarrow \text{BREAKTHROUGH}$

$T_{0.5\%} = 42 \text{ min}$

$T_{1.0\%} = 48 \text{ min}$

Quant Mod 10 0103 0125

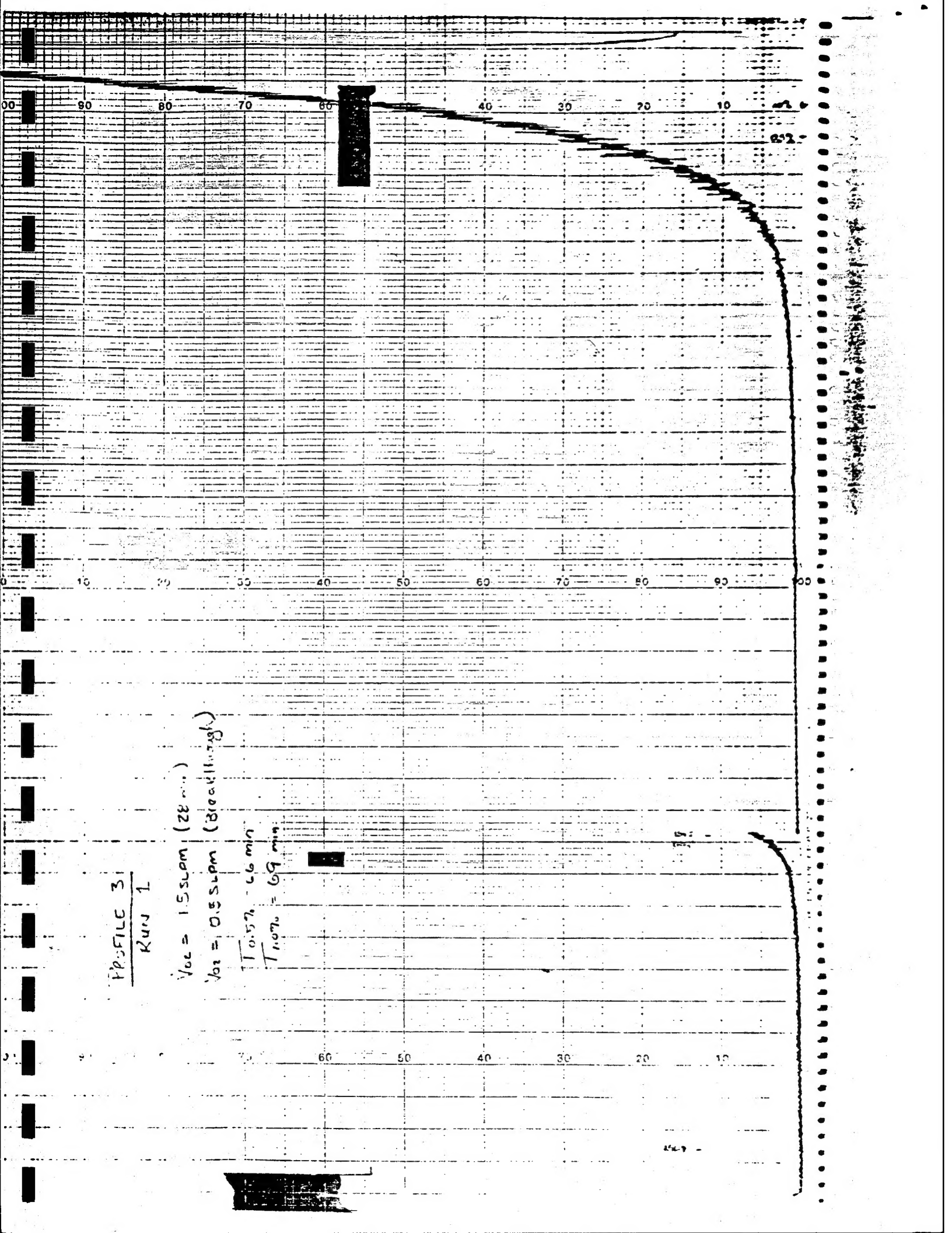
PROFILE 31
Run 1

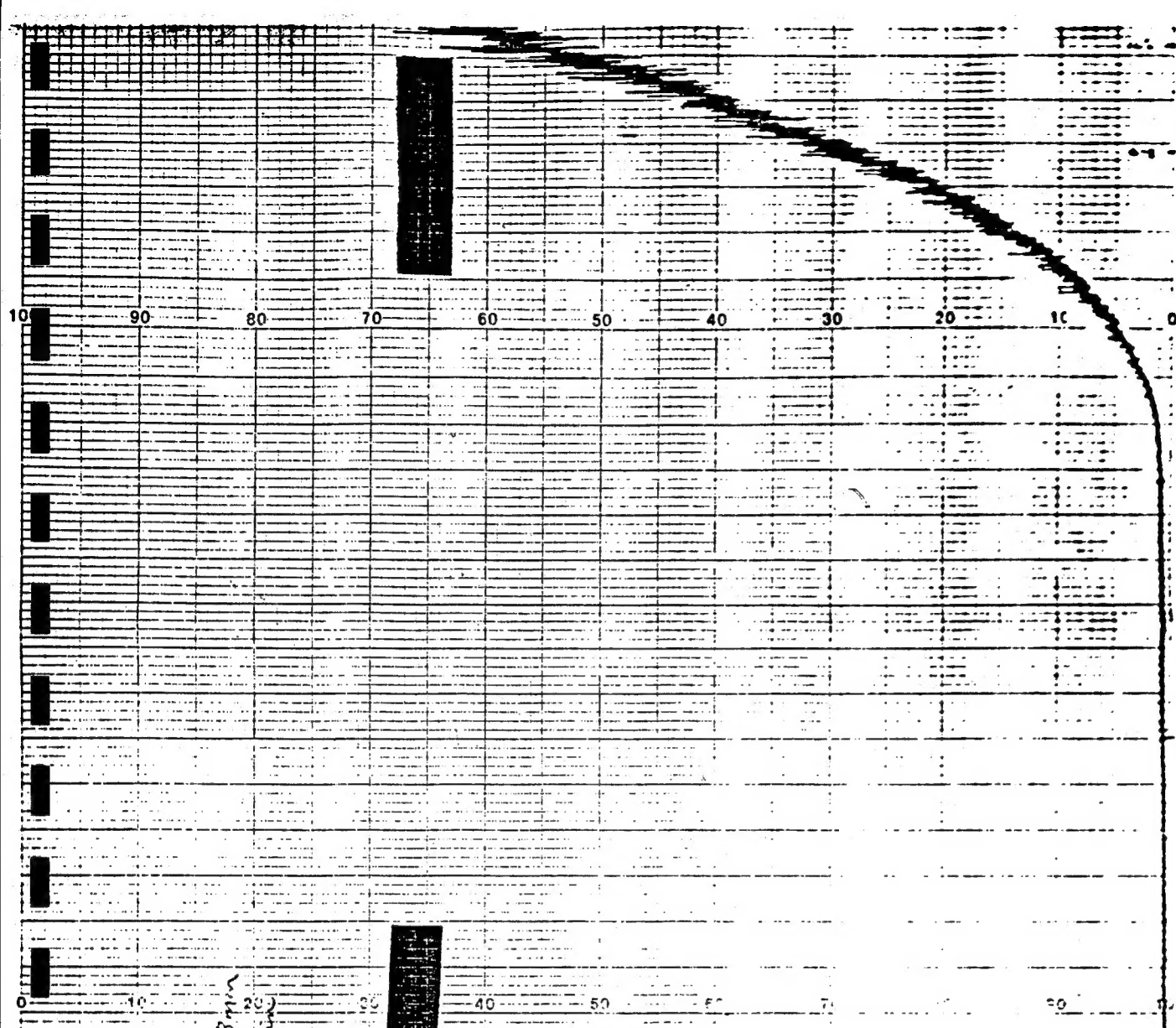
$V_{oc} = 1.55 \text{ uvm (28 min)}$

$V_{oc} = 0.55 \text{ uvm (Breakthrough)}$

$T_{0.5\%} = 66 \text{ min}$

$T_{1.0\%} = 69 \text{ min}$



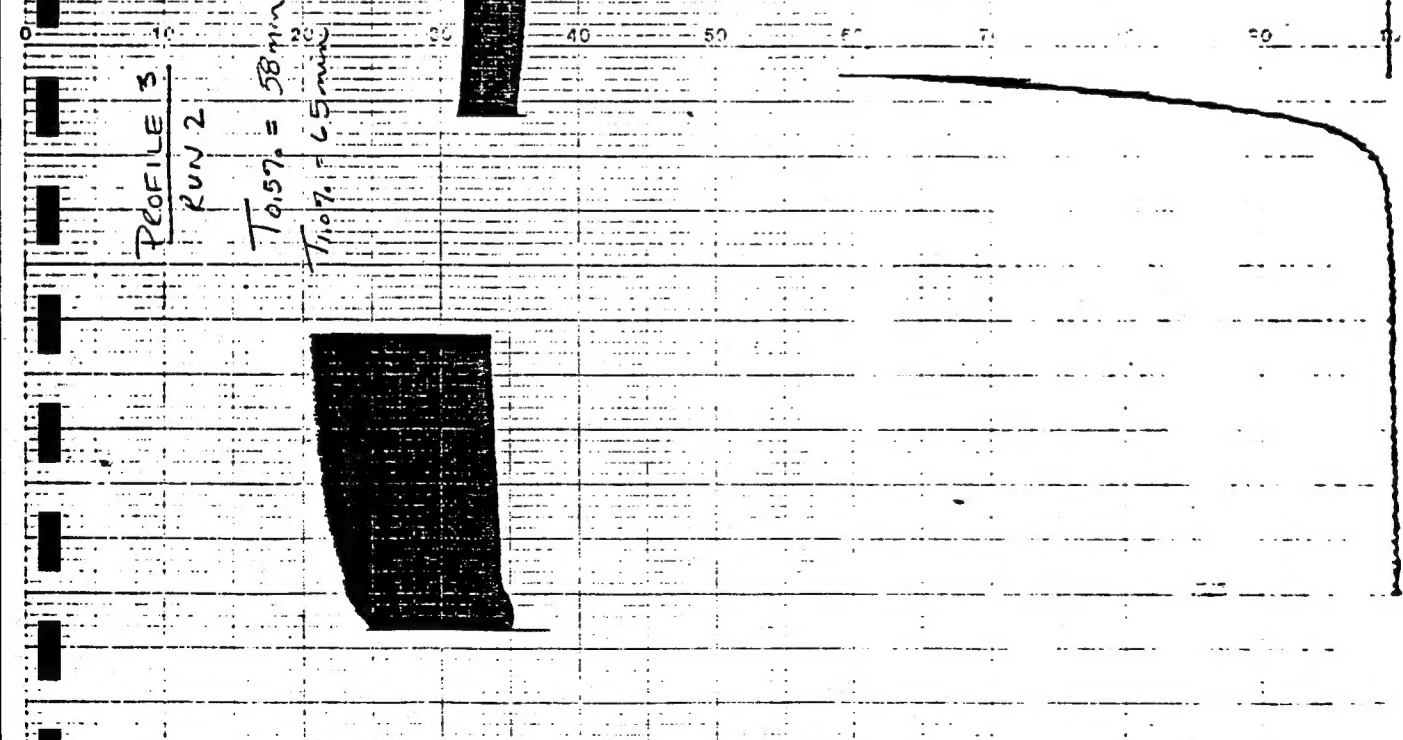


PROFILE 3

RUN 2

$T_{0.5\%} = 58 \text{ min}$

$T_{10\%} = 65 \text{ min}$



PROFILE 4

RUN 1

V_{O_2}

0.5 SLPM (23 min)

1.5 SLPM (Break thru)

$T_{0.5\%} = 18.5 \text{ min}$

$T_{1.0\%} = 20.5 \text{ min}$

0.47

V_{O_2} 0.5 SLPM

1.17

$V_{O_2} = 1.5 \text{ SLPM}$

0.51

1.07

PROFILE #4
(Run 2)

V_{O_2}

0.5 SLPM (18 min)

1.5 SLPM (Break thru)

$T_{0.5\%} = 16.5 \text{ min}$

$T_{1.0\%} = 18.5 \text{ min}$

DS1
6 min

DS1

1.0%
0.5%